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Energy Implications of Minienvironment in Clean Spaces: A Case Study on Minienvironment Energy End-use and Performance

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Contents

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A Case Study on Minienvironment Energy End-use and Performance

1. Background

Cleanroom air-recirculation systems typically account for a significant portion of the HVAC energy use in cleanrooms. High electric power density for fans to deliver airflows, defined as the fan's electric power demand divided by the cleanroom floor area, would normally be expected because of large volume of airflows that is designed, supplied, re-circulated, and exhausted within a given time. With the demand for better contamination control in specific applications, e.g., higher cleanliness within a localized and relatively small space, it is important to optimize the design of clean spaces as well as airflow. The optimization of airflow, layout, and sizing of clean spaces may potentially offer energy savings.

A minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment [1][2]. Such a minienvironment is normally used to maintain a level of stringent cleanliness in a tightened volume of clean spaces. Some minienvironments provide various device and physical configurations to actively or passively direct air from the surrounding cleanroom to and from the minienvironments. Some other minienvironments include independent temperature control, humidity control, and chemical filtration as part of their operation. For these, energy use can become more intensive. In order to understand energy saving implications, it is useful to obtain information on energy and environmental performance of minienvironments. At the same time, it is important to understand their design and field installation, and to identify potential energy-saving opportunities associated with minienvironments and cleanrooms.

This report summarizes a field study on the performance of a group of minienvironments installed in a semiconductor cleanroom facility. The report presents characteristic and performance information about the minienvironments and the cleanroom that encompassed the minienvironments. It also discusses energy-saving implications from applying the minienvironments, and opportunities in integrating minienvironments with the cleanroom as a way of achieving energy-savings. Based upon the findings and conclusions, this study identifies research gaps and recommendations for future work that is necessary to address the gap and to advance the design and operation of minienvironments in clean spaces. LBNL collaborated with PG&E to host a half-day workshop focused on minienvironments. A summary of the minienvironment workshop is included in the Appendix section of this final report.

2. Introduction

The purpose of a minienvironment is to achieve effective contamination control in a localized space, often through maintaining desired pressure differential or supplying unidirectional airflows needed for maintaining cleanliness levels within the space [1]. The dimensions of the minienvironment spaces may vary depending on specific applications. A recent research provided quantitative information on the performance of a minienvironment system [3][4]. A further study indicated that energy efficiency opportunities exist through optimizing design and operation of minienvironment air systems [5].

The advantages in using minienvironments include:

- Minienvironments may create cleanliness-class upgrade [6], better contamination control, and process integration.

- Minienvironments may maintain better contamination control by controlling pressure differentials or providing unidirectional airflows.

- Minienvironments may potentially reduce energy costs.

Past studies focused on design optimizing of minienvironments and contamination control [7][8][9] [10][11][12][13]. In addition, IEST publishes the methods or protocols on construction and operation of minienvironments [14][15][16]. Other studies or benchmarking activities addressed the impact of production yields by adopting minienvironments[17][18][19]. For example, a benchmarking study on minienvironments provided performance data but excluded information on the energy impact of minienvironments on the enclosing cleanroom facility [19]. Unfortunately, none of the above-mentioned studies [7-19] addressed energy issues associated with minienvironment applications, nor was quantitative data about energy performance provided in any of those studies.

Because minienvironments typically use fan-filter units, the energy intensity may be increased for the space served compared with similar cleanrooms without minienvironments. At the same time, appropriate integration of minienvironments with the surrounding cleanroom may also help to alleviate the overall electric power demand for the facility. A recent study quantified the electric power density of the air system in a minienvironment as a function of airflow speeds and pressure differential [5]. Corresponding to operating ranges for the minienvironment studied, electric power density ranged approximately from 17 W/ft^2 to 28 W/ft^2 (183 W/m^2 to 300 W/m^2) with the air speeds from 30 fpm to 110 fpm (0.15 m/s to 0.55 m/s). This range actually fell within the range of fan power density from previously measured ISO-Cleanliness-Class-4 cleanrooms, i.e., in the range of 16 W/ft^2 to 38 W/ft^2, or 172 W/m^2 to 409 W/m^2 [20][21].

With the goal of achieving the same cleanliness level within a minienvironment as that of the surrounding cleanroom, the airflow rate supplied to the minienvironment can be significantly lower than the airflow rate supplied to a full-scale cleanroom because of the significantly smaller volume of a minienvironment. This presents potential opportunities for energy savings when the required airflow rates for minienvironments could be reduced, i.e., the much smaller volumes of air that must be moved, conditioned, and filtered in a given time [3][4].

Prior to this study, virtually no quantitative data associated with the use of minienvironments in operation was available to quantify the actual energy-savings potential. In order to understand actual energy implications of incorporating minienvironments, it is necessary to quantify the magnitude of electric power demand or energy end-use of various minienvironments as well as that of the surrounding cleanroom, and to understand the overall energy implications of a cleanroom enclosing minienvironments.

3. Objectives

This case study was an investigation of the energy and environmental performance of a group of minienvironments in a cleanroom under normal operation. The main objective of this study is to develop field information to understand energy and environmental performance of minienvironments. This report provides discussion of energy-savings potential from adopting minienvironments for contamination control and improving the energy efficiency of minienvironment systems. The information and recommendations developed from this study can be used to identify energy-savings potential, research gaps, and future investigations in achieving efficient and effective (E^2) minienvironments in the industries that use them.

Specifically, the technical objectives of this study include:

1) Understand the energy and environmental performance of the minienvironment systems.

2) Compare the energy performance of the minienvironments and that of cleanrooms.

3) Discuss and estimate energy-savings potential by applying energy-efficient minienvironments within cleanrooms for effective contamination control.

4) Identify research gaps and develop recommendations for future research and investigations.

4. Approach

A minienvironment is used to maintain a certain cleanliness level by controlling the particle concentration in the localized space. In this study, various localized spaces within an ISO-Cleanliness-Class-4 cleanroom were installed and used to achieve a cleanliness level equivalent to that of an ISO-Cleanliness-Class-3 or Class-4 clean space.

In the cleanroom, there were various activities that required different environmental conditions depending on the process or locality within the cleanroom, i.e., ISO-Cleanliness-Class-3 and/or ISO-Cleanliness-Class-4 localized spaces. A number of minienvironments with a cleanliness level equivalent to ISO-Cleanliness-Class-3 spaces in the cleanroom were installed in the facility. Specifically, these stand-alone, self-powered minienvironments were used to provide filtered air through localized HEPA or ULPA filters at certain airflow speeds for various processes or product-testing activities. Another group of minienvironments within the same ISO-Cleanliness-Class-4 cleanroom was designed and installed to provide physical barriers and they contained no additional fan-powered device such as a fan-filter unit. These passive, non-fan-powered minienvironments were used to present physical barriers so as to isolate the process and activities from contamination, which could be affected by unexpected changes in ambient conditions, local disturbance of airflow patterns, or pollutants from the human occupants working in the ISO-Cleanliness-Class-4 cleanroom that housed the minienvironments.

The measured parameters included electric power demand (representing energy end-use), airflow rates, air pressures, and particle concentrations in and around the minienvironments under normal operating conditions. The information developed in this case study included electric power demand of five different stand-alone, fan-powered minienvironments, the energy performance of these minienvironments, and the effectiveness of contamination control in such device. Key performance metrics were developed and calculated to characterize the overall performance of the minienvironments. This study also compared the performance of the five minienvironments with that of the enclosing cleanroom and other cleanrooms that were previously studied. Based upon the measured data, the study discussed and estimated the potential energy-savings from implementing energy-efficient minienvironments.

4.1 Electric Power Demand

The power meter used in this study was a true RMS energy analyzer with a measurement uncertainty of ±3% [22]. The meter recorded the electric current, voltage, power factor, the actual power supplied to the air delivery systems of the minienvironments in the cleanroom, and the power supplied to the air-handling-unit systems for the cleanroom. The power meter was used with various current transducers (uncertainty ±2%) and voltage transducers to measure the electric current, voltage, power factor, and actual power demand of the air delivery systems. The air delivery systems were the fan-filter units (FFUs) serving the five ISO-Cleanliness-Class-3 minienvironments, and two types of air-handling units serving the ISO-Cleanliness-Class-4 cleanroom. The measured power demand was used to quantify the energy performance of the air systems for the operating minienvironments as well as that of the cleanroom.

4.2 Airflow Speed and Pressure Differential

A backpressure-compensated device attached to an electronic micro-manometer [23] measured the average speeds of the airflow delivered out of the face of the fan-filter units, which were installed at the top of the stand-alone minienvironments. The actual sizes of individual FFUs and HEPA filters varied from minienvironment to minienvironment.

The measurement uncertainty in airflow speeds was ± 3% of reading plus ± 7 fpm (3.5 cm/s) from 50 to 2500 fpm (0.25 m/s to 12.5 m/s). An airflow measurement device was used to sample 16 points over a 1 ft x1 ft (30 cm x 30 cm) area to determine average airflow speeds at a distance of 2.5 inches (6.3 cm) downstream away from the face of the filter frames. Airflow-speed readings were automatically corrected for the density effect of barometric pressure and temperature. Readings were displayed as local density and true air speeds.

Pressures were measured using a Pitot tube with a multi-meter. The multi-meter measures a wide range of pressures from 0.0001-inch-water column (0.025 Pa) to over 60.00-inch-water column (15,000 Pa), with a measurement uncertainty of ±2% of reading plus 0.001-inch-water column (0.25 Pa) from 0.05-inch-water column to 50.00-inch-water column (0.125 Pa to 12,500 Pa). The air pressure differential between the space inside the minienvironment and the space surrounding the minienvironment was recorded for each minienvironment, concurrent to the airflow measurements under the normal operating conditions.

4.3 Particle Concentration

In addition to measuring electric power demand, airflow speeds, air pressure differential between the space inside the minienvironments and the space surrounding the minienvironments, particle concentration levels were measured concurrently to evaluate environmental performance of the minienvironments, i.e., particle concentration inside and outside of the minienvironments.

According to the definition of Airborne Particulate Cleanliness Classes in ISO Standard 14644 [6], the classification of air cleanliness in cleanrooms and associated controlled environments is defined in terms of concentration of airborne particles within the space. For example, a cleanroom with an ISO-Cleanliness-Class-4 level corresponds to no more than 10,000 counts of particles per cubic meter with particle sizes of 0.1-µm or larger, or 352 counts of particles per cubic meter with particle sizes of 0.5-µm or larger, in the space of concern. Using this concept, a minienvironment with an ISO-Cleanliness-Class-3 level corresponds to no more than 1,000 counts of particles sizing 0.1-µm or larger per cubic meter, or 35 counts of particles sizing 0.5-µm or larger per cubic meter, of the minienvironment space.

Laser particle counters [24] were used to measure the particle concentration within the minienvironments. The laser-based particle counter discriminated and counted particles with sizes of 0.1-µm, 0.2-µm, 0.3-µm, 0.5-µm, 1.0-µm, and 3.0-µm. The airflow rate used for particle sampling was 2 cfm (56.6 L/min) supplied by an internal carbon-vane pump in the counters. In general, a higher airflow rate for particle sampling in the chamber of a particle counter indicates higher capacity of sensing particles traveling into the counter and better accuracy in particle counts during transitional (or unsteady-state) sampling.

5. Results

5.1 Characteristics of the cleanroom

The cleanroom housing the minienvironments in this study was located on the second floor of a two-story semiconductor manufacturing facility in Southern California. The ISO-Cleanliness-Class-4 cleanroom had a total floor area of 4,065 ft^2 (378 m^2) with a ceiling height of 10 ft (3.0 m), and operated 24 hours a day and 365 days a year. In addition to one make-up air system, two types of recirculation air systems served the cleanroom: ducted-HEPA-filter and pressurized-plenum.

The fans in the recirculation air-handling units for the cleanroom were originally designed to deal with possible future expansion, which was expected during the original design and installation. For example, in the original design, airflow rates for recirculation consisted of a) 216,000 cfm (2,702 m^3/min) to be supplied through a total of four air-handling units (176 kW) connected to the ducted-HEPA filters, and b) 131,100 cfm (1,811 m^3/min) to be supplied by a total of three additional air-handling units (121 kW) connected to the pressurized plenum.

The air-handling units connected to the ducted-HEPA-filter systems were designed to cover approximately 2,290 ft^2 (213 m^2) of the primary cleanroom space[1], while the other three-air-handling units serving the pressurized plenum covered approximately 1,390 ft^2 (129 m^2) of the primary cleanroom space. The total floor area of the primary cleanroom space was 3,680 ft^2 (or 342 m^2). The cleanroom had a secondary space for return air, which covered a floor area of approximately 385 ft^2 (36 m^2).

Table 1 shows the physical size of the cleanroom, airflow rates, electric power demand, air-system efficiency, air-change rate, and electric power density for the air-recirculation systems, and make-up-air systems in its normal operation.

Table 1 Cleanroom airflows and electric power demand

Air-handling Systems in ISO Class 4 Cleanroom	Units	Recirculation Air (Ducted HEPA Filters)	Recirculation Air (Pressurized Plenum)	Recirculation Air (Combined)	Make-up Air
Floor Area Served	m^2	213	129	342	342
	ft^2	2,290	1,390	3,680	3,680
Airflow Rate	m^3/min	2,702	1,811	4,513	424
	cfm	95,406	63,963	159,369	14,960
Electric Power	kW	24	13	38	11
Airflow Rate per Power Demand	m^3/min/W	0.11	0.14	0.12	0.04
	cfm/kW	3,915	4,871	4,250	1,324
Average Cleanroom Airflow Speed	m/s	0.21	0.23	0.22	0.02
	feet per minute (FPM)	42	46	43	-
Air-change Rate	m^3air/(hr-m^3room)	250	276	260	24
	ft^3air/(hr-ft^3room)	250	276	260	24
Electric Power Density	W/m^2	115	102	110	33
	W/ft^2	11	9	10	3

In actual operation, the airflow rates from the ducted-HEPA-filter systems and the pressurized-plenum systems were measured to be 95,406 cfm (2,702 m^3/min) and 63,963 cfm (1,811 m^3/min), respectively. The total of the actual recirculation airflow rate was 159,369 cfm (4,513 m^3/min), which was about 46% of the design airflow rate. This corresponded to the fan power of 38 kW, which was approximately 13% of the designed fan power for recirculation air. The average of measured recirculation-fan power density for the cleanroom was approximately 10 W/ft^2 (110 W/m^2), which was lower than the designed 81 W/ft^2 (872 W/m^2). Apparently, the

[1] Note: The floor area served is listed as estimation based upon the assumption that both the ducted-HEPA systems and pressurized-plenum systems provided the same airflow speed at the design condition.

fan motors were oversized and therefore the air recirculation probably induced a much lower pressure drop within the systems than designed.

The overall recirculation airflow rate per fan power demand was 4,250 cfm/kW (0.12 m^3/min/W), which was about three times higher than the design (1,165 cfm/kW, or 0.03 m^3/min/W). Overall, the average cleanroom airflow speed was 43 fpm (or 0.22 m/s) compared to the design value of 94 fpm (or 0.47 m/s), with a recirculation-air-change rate of 260 air-volume/hr-room-volume (260 m^3air/hr-m^3room).

5.2 Characteristics of the minienvironments

The minienvironments in this study were partially enclosed spaces in the ISO-Cleanliness-Class-4 cleanroom. Two types of minienvironments were identified in this cleanroom:

1) A stand-alone minienvironment with an open-loop air system, within which airflow was drawn from the surrounding cleanroom space, through fan-filter units that were attached at the top of the minienvironment. The filtered air was then supplied into the minienvironment to maintain a higher cleanliness level within the localized space, i.e., ISO-Cleanliness-Class-3 space.

2) A passive minienvironment to which no additional fan was attached. This was contrary to the case for fan-filter units on top of a stand-alone minienvironment. A passive minienvironment mainly served as physical barriers to provide a buffer zone from the surrounding space to minimize external disturbance. Normally without any additional filter, it was used to maintain a cleanliness level within the separate minienvironment, i.e., ISO-Cleanliness-Class-4 space.

A schematic diagram of the minienvironments in the cleanroom is included in the Appendices of this report. In a stand-alone, open-loop minienvironment, the supply air was filtered through FFUs located on top of the minienvironment. Additional flow shields were installed underneath the HEPA filters of the FFUs to create downward unidirectional airflows inside the minienvironment. The outgoing airflows from the minienvironment may then mix with the surrounding air within the cleanroom space.

Because a passive minienvironment did not directly affect overall electric power demand for airflow delivery to the minienvironment, this study focused only on a group of stand-alone, open-loop minienvironment systems.

Table 2 shows the physical size of the inner-space of the stand-alone, open-loop minienvironments that were selected and measured in this study.

Table 2 Characteristics of Sample Minienvironments

Minienvironments	Units	A	B	C	D	E
Floor Area	m^2	6.3	1.2	1.7	0.7	4.1
	ft^2	68	13	18	8	44
Height	cm	178	259	230	216	240
	inch	70	102	91	85	95

Overall, eight minienvironments with the size equivalent to that of "A" listed in were located in the ISO-Cleanliness-Class-4 cleanroom. Among these, five minienvironments were stand-alone, open-looped systems that were designed to create ISO-Cleanliness-Class-3 spaces, while three others were passive minienvironments without fans to deliver the airflow from the cleanroom into the minienvironments. Additional minienvironments, including minienvironments B, C, D, and E, were located within the same cleanroom. The total of net floor area of the stand-alone, open-looped minienvironments was estimated as approximately 424 ft^2 (39 m^2), which represented approximately 12% of the cleanroom's primary floor area.

5.3 Minienvironment Energy Performance

The operating efficiency of the FFUs in the minienvironments can vary considerably at various operating conditions. Optimizing the airflow speed and air pressure in a minienvironment not only can improve FFU operating efficiency, but also may improve space cleanliness, noise and vibration characteristics, and operating life of the fans.

The minienvironments normally operated continuously - 24 hours a day and seven days a week. Spot measurements were taken at the five minienvironments that were selected to quantify and evaluate their energy and environmental performance.

Table 3 shows the measurement results including airflow rate, airflow speed, electric power, air-system efficiency, energy performance index (EPI), air-change rate, and electric power density for the five minienvironments.

Table 3 Minienvironment airflow and electric power demand

Minienvironments	Units	A	B	C	D	E	A-E Sum	Average
Airflow Rate	m^3/min	141	21	26	22	106	317	-
	cfm	4,988	745	927	792	3,730	11,182	-
Electric Power	kW	2.1	0.4	0.4	0.3	1.1	4.3	-
Airflow Rate per Power Demand	m^3/min/W	0.07	0.06	0.06	0.09	0.09	-	0.07
	cfm/kW	2,353	1,961	2,250	3,106	3,272	-	2,588
EPI	W/(m^3/min)	15.0	18.0	15.7	11.4	10.8	-	14.2
	W/cfm	0.43	0.51	0.44	0.32	0.31	-	0.40
Average Airflow Speed	m/s	0.37	0.30	0.26	0.50	0.43		0.37
	fpm	73	58	52	99	84	-	73
Air-change Rate	m^3air/(hr-m^3room)	752	412	410	839	642	-	611
Electric Power Density	W/m^2	335	320	246	343	277	-	304
	W/ft^2	31	30	23	32	26	-	28

5.3.1 Airflows and Air-Change Rates

For the selected minienvironments within the ISO-Cleanliness-Class-4 space, the recirculation air was supplied to through the FFUs to the minienvironments.

While there were variations in the floor area of the minienvironments ranging from eight ft^2 to 68 ft^2 (0.7 m^2 to 6.3 m^2), the minienvironments exhibited a wider range of airflow rates, namely, ranging significantly from 745 cfm to 4,988 cfm (21 m^3/min to 141 m^3/min) [Table 3]. This wide variation in airflow rates was also due to different airflow speeds in various minienvironments, in addition to the various floor areas.

The average airflow speed inside each minienvironment ranged from 52 fpm to 99 fpm (or 0.27 m/s to 0.50 m/s), with an average of 73 fpm (or 0.37 m/s). The airflow speeds were generally higher than the average airflow speed in the surrounding cleanroom, which was 43 fpm (or 0.22 m/s) as shown in Table 1.

The air-change rates of the five minienvironments differed from 410 m^3air/hr-m^3room to 752 m^3air/hr-m^3room, exhibiting a similar range to the operating range of a typical stand-alone, open-looped minienvironment in a previous study [3][4]. In that study, the operating range of air-change rates for the minienvironment was between 480 m^3air/hr-m^3room and 800 m^3air/hr-m^3room, corresponding to airflow speeds ranging from 60 fpm to 100 fpm (or 0.30 m/s to 0.50 m/s) in the minienvironment.

In summary, the air-change rates of the five minienvironments tested in this study were significantly higher than that of the ISO-Cleanliness-Class-4 cleanroom housing the minienvironments, i.e., 260 m^3air/hr-m^3room.

As shown in Figure 1, it is clear that higher average airflow speeds, higher HEPA/ULPA filter coverage in the five minienvironments (i.e., 100%), and lower ceiling heights of the minienvironments collectively contributed to the higher air-change rates within the minienvironments than that of the surrounding cleanroom.

When compared with the average airflow speeds in other ISO-Cleanliness-Class-4 cleanrooms from a previous study [20], the magnitude of airflow speeds from these ISO-Cleanliness-Class-3 minienvironments generally exhibited a similar or lower range. In addition, within similar airflow speed range, the air-change rates of the five minienvironments exhibited a slightly wider range than that of ISO-Cleanliness-Class-4 cleanrooms, which was between 385 and 680 m^3air/hr-m^3room corresponding to airflow speeds ranging from approximately 60 fpm to 120 fpm (or 0.30 m/s to 0.60 m/s) [20]. In general, the HEPA/ULPA filter coverage in the minienvironments was 100% while the ISO-Cleanliness-Class-4 or ISO-Cleanliness-Class-5 cleanrooms could have a lower coverage.

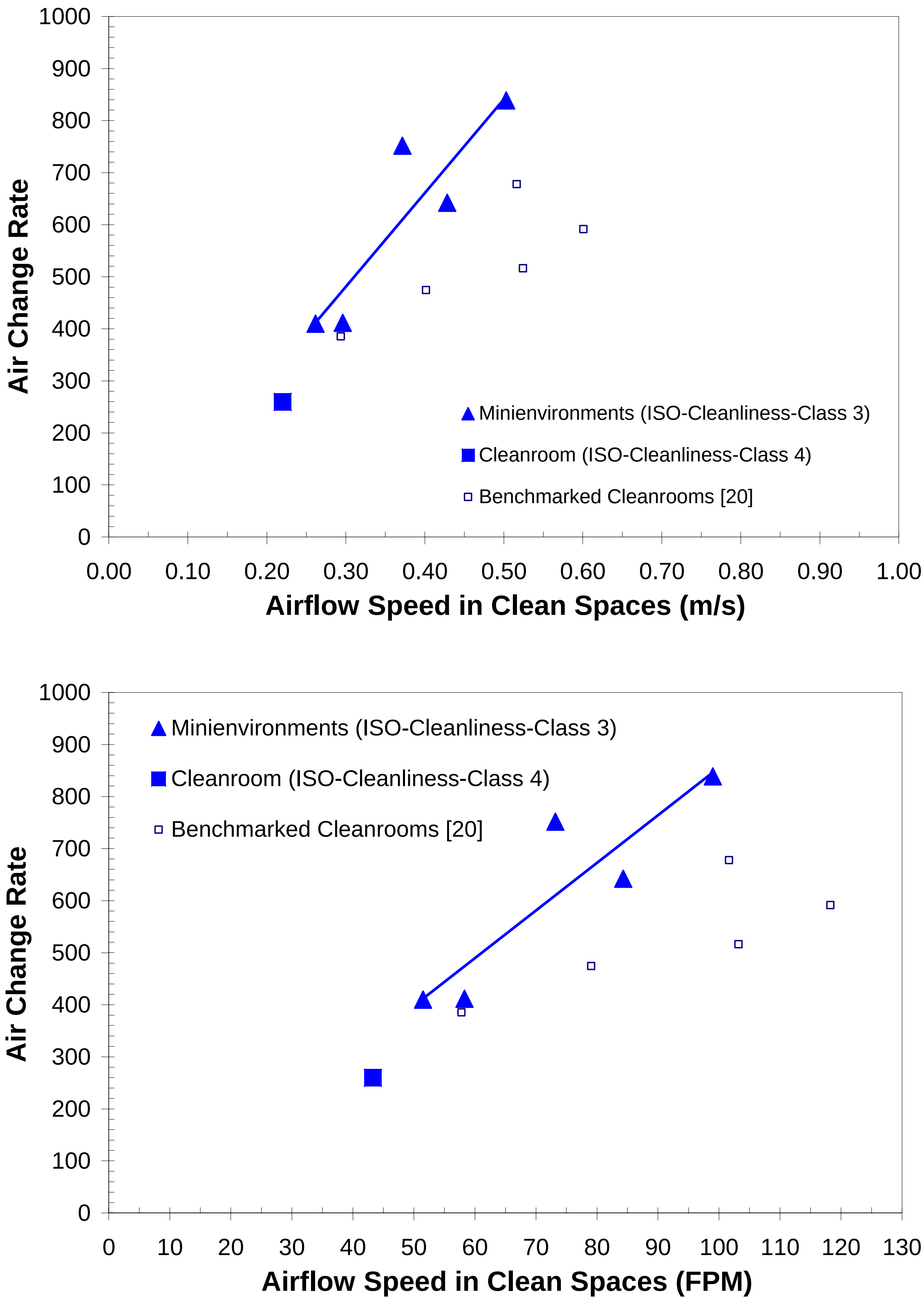


Figure 1 Air Change Rates and Airflow Speed

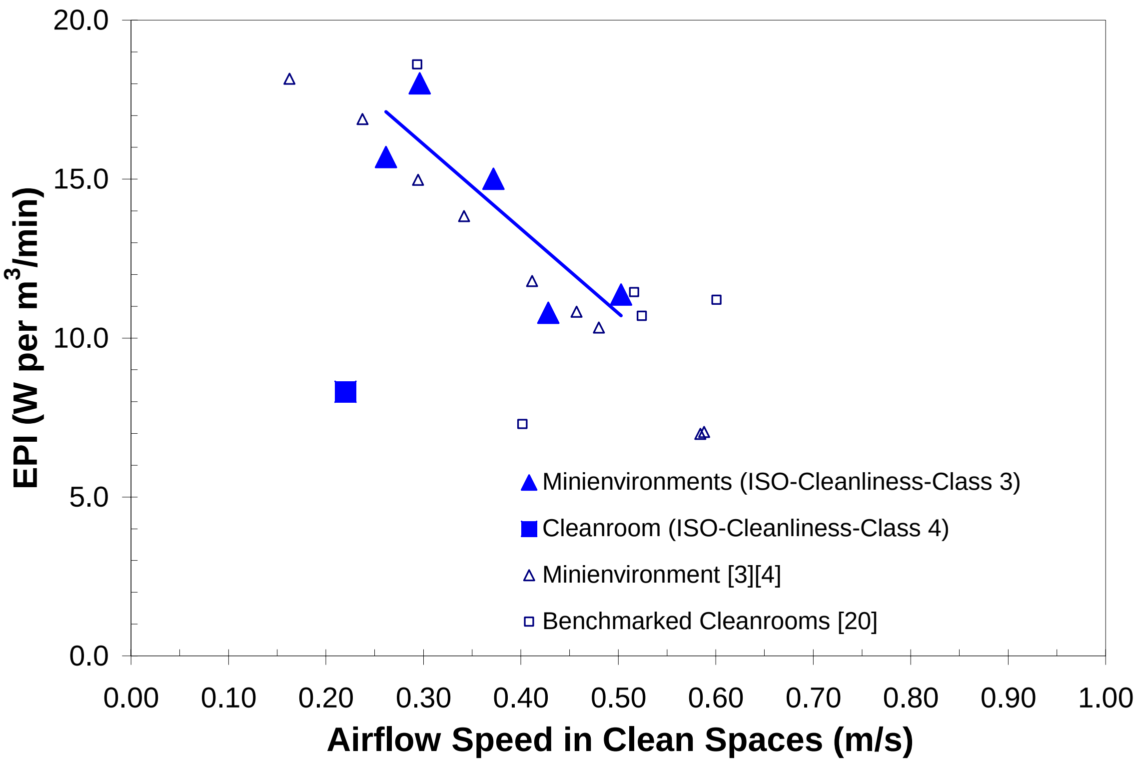
5.3.2 Energy Performance Index (EPI)

The energy performance index (EPI) of a minienvironment's air system is defined as the total electric power supplied to the fan system divided by the airflow rate in the minienvironment [3][4]. A higher EPI value under the same operating condition means that more electric power is demanded for supplying the same airflow rate to the minienvironment, thus corresponding to lower energy efficiency of air-delivery systems in the minienvironment.

Figure 2 shows the measured EPI values of the five minienvironment systems compared to that of the surrounding cleanroom (ISO-Cleanliness-Class 4). The air systems' EPI values of the five minienvironments (designed as ISO-Cleanliness-Class 3) showed a wide range, i.e., ranging from 0.31 W/cfm to 0.51 W/cfm (10.8 W per m^3/min to 18.0 W per m^3/min), corresponding to the airflow speeds ranging from approximately 52 fpm to 99 fpm (or 0.27 m/s to 0.50 m/s). In addition, the EPI values of the ISO-Cleanliness-Class-3 minienvironments were consistently higher than the surrounding ISO-Cleanliness-Class-4 cleanroom, of which the EPI value was 0.24 W/cfm (8.5 W per m^3/min) corresponding with a lower airflow speed.

It is clear that the EPI values among these minienvironments tended to decrease with the increase in the airflow speed (or airflow rates normalized by minienvironment floor area) inside the minienvironments. This trend indicates that within the measured operating range, lower EPI values (more efficient in delivering the air) tended to correlate with higher airflow speeds among the five minienvironments. This trend was similar to the finding from a previous study on a typical stand-alone, open-looped minienvironment system, which exhibited an operating range from 60 fpm to 100 fpm (or 0.30 m/s to 0.50 m/s) in the minienvironment [3][4]. However, EPI values of the minienvironments in this study were slightly higher when compared with that of the other minienvironment operating with the similar airflow speeds [3][4].

Figure 2 also includes the measured EPI values for the various ISO-Cleanliness-Class-4 cleanrooms that were previously studied [20], which ranged between 0.21 W/cfm to 0.53 W/cfm (7.4 to 18.7 W per m^3/min). The EPI values for the minienvironments, which generally operated at a similar or lower airflow speed, were generally higher than those of the cleanrooms.



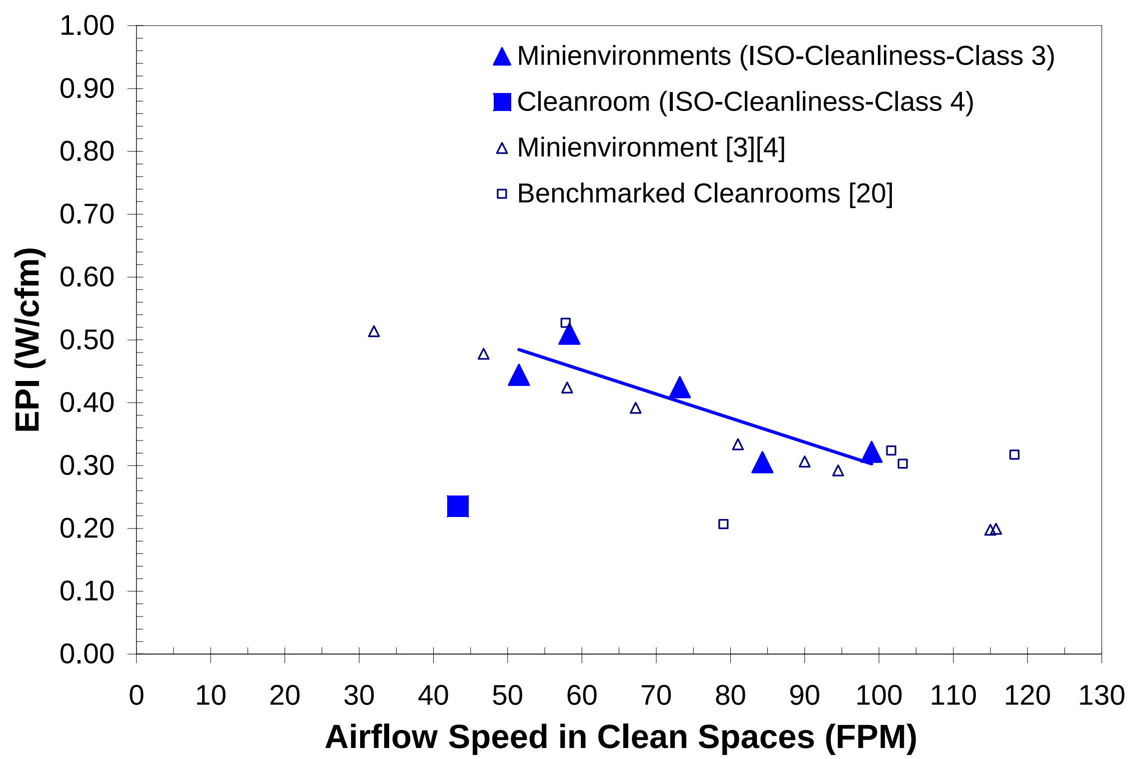


Figure 2 Energy Performance Index and Airflow Speed

5.3.3 Electric Power Density

Electric power density is defined as the electric power demand, which is required for supplying airflow to the clean space such as a minienvironment or a cleanroom, divided by the floor area of the primary clean space intended for contamination control, i.e., floor area of an individual minienvironment or the primary floor area of a cleanroom.

Figure 3 shows the electric power density of the air systems for the five ISO-Cleanliness-Class-3 minienvironments and the air-recirculation fans serving the ISO-Cleanliness-Class-4 cleanroom in this study.

The air-recirculation systems of the ISO-Cleanliness-Class-4 cleanroom in this study included pressurized-plenum and ducted-HEPA recirculation air systems. They collectively exhibited a much lower level of electric fan-power density that those of the minienvironments. Specifically, the electric power density of the air supply systems for five minienvironments ranged from 26 W/ft^2 to 32 W/ft^2 (280 W/m^2 to 344 W/m^2) with an average of 28.3 W/ft^2 (304 W/m^2), while the electric power density of the air-recirculation fans for the ISO-Cleanliness-Class-4 cleanroom was 10.2 W/ft^2 (110 W/m^2). In addition, each value of the electric power density correlated with an average airflow speed inside the clean space. The higher electric power density of the minienvironments corresponded to the airflow speeds ranging from approximately 52 fpm to 99 fpm (or 0.27 m/s to 0.50 m/s), while the lower electric power density of the cleanroom corresponded to an average airflow speed of 43 fpm (0.22 m/s) in the cleanroom. A combination of the following reasons probably contributed to the higher power density in the minienvironments:

- The average airflow speeds in the minienvironments were higher than the average air speed in the surrounding cleanroom.

- The stand-alone minienvironment air systems (FFU systems) with smaller fans were less energy-efficient in delivering air to the intended space, compared to the air-recirculation systems consisting of pressurized-plenum or ducted-HEPA systems typically with larger fans serving the cleanroom.

- The ceiling of all minienvironments was fully covered by the HEPA filters while the ceiling of the enclosed cleanroom was not fully covered by HEPA filters.

It is clear that the electric-power-density values of the minienvironments tended to increase with the increase in the delivered airflow speed (or airflow rate divided by minienvironment floor area) inside the minienvironments. This trend indicates that within the measured operating range, higher values of electric-power-density for the minienvironments (more energy intensive in delivering the air) correlated to higher airflow speeds in the minienvironments. This trend was similar to the finding from a previous study on a minienvironment [3][4] within a certain airflow range (i.e., up to 0.50 m/s).

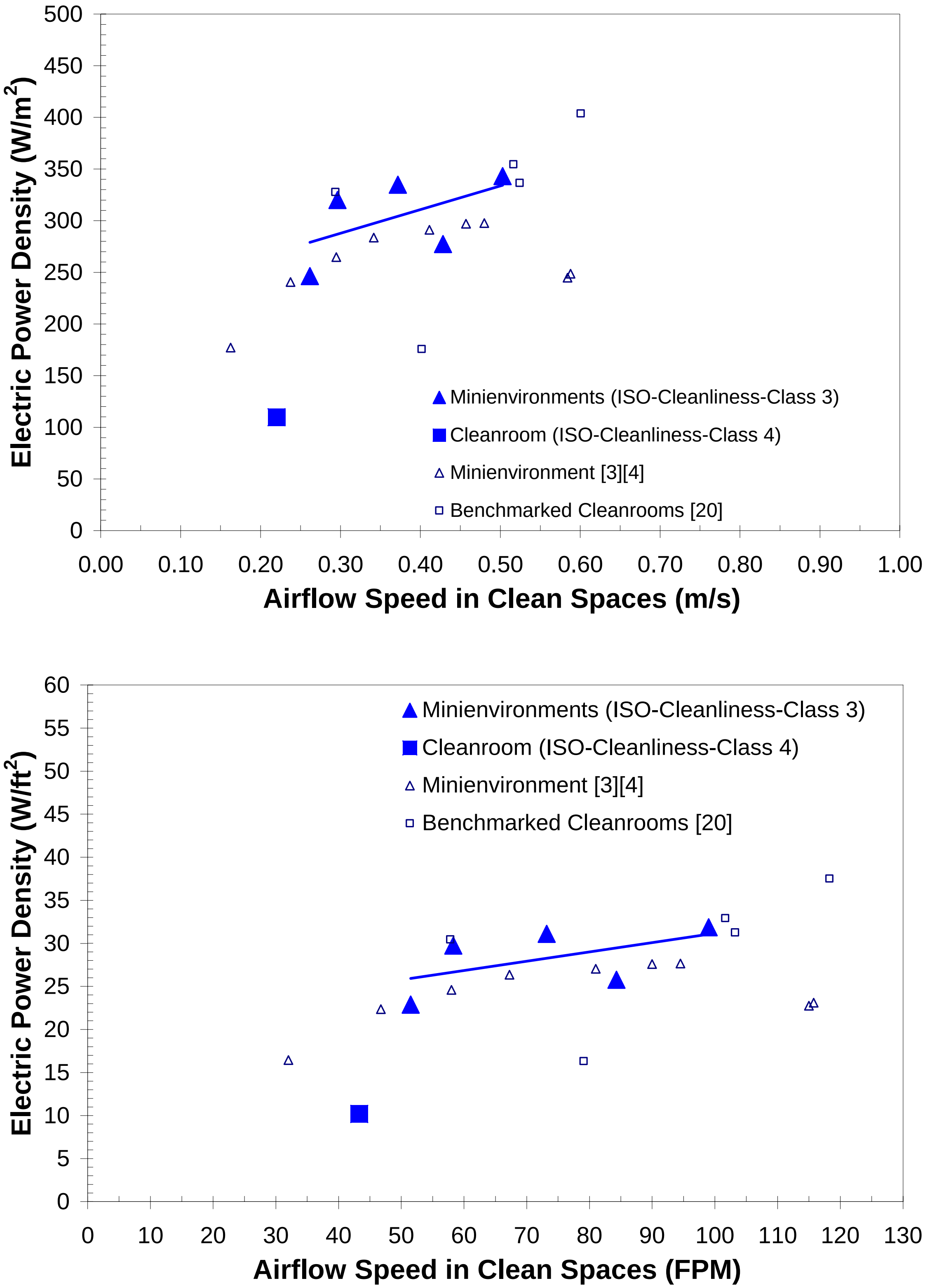


Figure 3. Electric Power Density and Airflow Speeds for Five Different Minienvironments and the surrounding Cleanroom

Furthermore, the figure also includes the electric power density of the air systems reported in previous studies [3][4][20]. While the air-recirculation systems of the ISO-Cleanliness-Class-4 cleanroom in this study collectively exhibited a much lower level of electric fan-power density that those of the minienvironments, they appeared to have lower fan-power density when compared with the group of ISO-Cleanliness-Class-4 cleanrooms with a range of 16 W/ft^2 to 38 W/ft^2 (172 to 409 W/m^2) in a previous study [20]. Those cleanrooms were operating at airflow speeds ranging from 80 fpm to 120 fpm (or 0.40 m/s to 0.60/m/s), higher than the average speed of 43 fpm (0.22 m/s) for the ISO-Cleanliness-Class-4 cleanroom in the current study.

It is also clear that the electric-power-density values of most minienvironments in this study were slightly higher when compared with that of the other minienvironment under the similar range of airflow speeds [3][4]. Given that electric power density of FFU device typically ranged from 20 W/ft2 to 33 W/ft^2 (215 W/m^2 to 355 W/m^2) at the airflow speeds in the vicinity of 50 fpm (0.25 m/s) [25], the minienvironments in this study exhibited similar power density levels of some of the fan-filter units.

In summary, the actual performance data shown in Figure 3 suggests that 1) within the range of airflow speeds measured from the five minienvironments (52 fpm to 99 fpm, or 0.27 m/s to 0.50 m/s), the electric power density of minienvironments typically increased with the increase of average airflow speeds; and 2) the electric power density of the five minienvironments were higher than that of cleanrooms. This indicates that there could be opportunities in optimizing the efficiency of the fan-filter units in the minienvironments, such as optimizing airflow speeds in addition to improve the unit's efficiency. Theses should result in energy-savings in minienvironment operation. Magnitudes of savings potential are estimated in the discussion section of this report.

5.4 Minienvironment Environmental Performance

The purpose of a minienvironment is to provide contamination control through physical barriers, and use filtration to locally control the particle concentration below a certain level within the minienvironment space. It is important to ensure that the enclosed space achieves the required cleanliness class.

The filtration efficiency of HEPA/ULPA filters could be affected by airflow speeds, the design, geometry, and material of filters used in the minienvironment [4]. Optimal contamination control for minienvironments can be realized by regulating airflow rates and air pressure differentials between the minienvironment space and its surrounding space. The benefits of optimal contamination control would include improved effectiveness and efficiency of particulate filtration control.

In common practice, maintaining positive air pressure in a minienvironment relative to the air in the surrounding space may prevent the less-clean air from being transported to the minienvironment and therefore contaminating the process inside the minienvironment.

In the five minienvironments studied, the pressure differential and particle concentration was measured. Table 4 shows the measured results for minienvironments A through E.

Table 4 Minienvironment Environmental Performances

Minienvironments	Units	A	B	C	D	E
Pressure Differential	**Pascal**	0.15	0.15	0.025	0.025	0.175
	Inch water column	0.0006	0.0006	0.0001	0.0001	0.0007
Space Volume	**m^3**	11.3	3.1	3.8	1.6	9.9
	ft^3	398	109	136	57	348
Particle Concentration within Minienvironment	**Particle count per cubic meter**	0	0	0	0	0

5.4.1 Pressure Differential

The pressure differential is the air-pressure difference between minienvironment's internal space and its surrounding space. By adjusting the airflow rates, a positive pressure differential for minienvironments may be created to prevent introduction of potential contaminants from the surrounding cleanroom.

Table 4 shows that the measured pressure differential ranged from 0.025 Pa to 0.175 Pa among the five minienvironments. This was lower by several levels of magnitude when compared to the recommended ranges [1], which recommends a typical process-bay pressure exceeding the service-chase pressure by 0.01- to 0.05-inch-water column (or 2.5 Pa to 12.5 Pa) in microelectronic minienvironments. In addition, the measured pressure differential was also much lower than the rule-of-thumb pressure differential with a minimal value of 0.01- to 0.03-inch-water column (or 2.5 Pa to 7.5 Pa).

In a recent minienvironment study, the pressure differential ranged from 0.003-inch-water column to 0.024-inch-water column (0.75 Pa to 6 Pa) [4], corresponding to airflow speeds ranging from 32 fpm to 95 fpm (or 0.16 m/s to 0.48 m/s). It is apparent that the actual pressure differential between each minienvironment and the enclosing cleanroom was much lower than the recommended range or the rule of thumb. This was due to large open areas for outgoing airflows through the minienvironments. The observed operation was largely dependent on the function or design of the minienvironment. Less opening area could be achievable by the use of closeable doors at the local area but it was not adopted at the facility site studied.

In summary, while the spot measurements of pressure differential might not be sufficient to represent overall pressure distribution or control for the minienvironments studied, the findings however illustrated that the rule of thumb and the IEST Recommended Practice for the pressure differential in minienvironments may have suggested a higher range than necessary for some of the minienvironment applications. Additional research should look into how to better record and measure spatial pressure distributions over time, and document the acceptable range of pressure differentials in minienvironments.

5.4.2 Particle Concentration

Particle concentration was measured for particles with the sizes ranging from 0.1 micron-meter to three micron-meters within the five minienvironments studied. The particle counter was set to run 30-second samples with a 3-second delay between samples. The sampled particle counts per space volume were then averaged as reported in Table 4. The measurable concentration was rounded as zero. This was below the particle concentration thresholds for minienvironments with ISO-Cleanliness-Class-3 rating, i.e., no more than 1,000 counts of 0.1-µm particles per cubic meter, or 35 counts of 0.5-µm particles per cubic meter, of the minienvironment space [6]. This indicates that the five minienvironments that were tested all satisfied or even surpassed the minimal environmental requirements for ISO-Cleanliness-Class 3 at the time of particle measurements.

In this case study, supplying and controlling the measured airflow rates through the HEPA filters of the fan-filter units in the minienvironment was sufficient to maintain particle concentration within the required range for the ISO-Cleanliness-Class 3 spaces, even though the actual pressure differential between each minienvironment and the enclosing cleanroom was much lower than the IEST recommended range or the rule of thumb.

6. Discussion

Based upon the measurements in this case study, the average of electric power density of the selected sample ISO-Cleanliness-Class-3 minienvironments was 28.3 W/ft^2 (or 304 W/m^2), while the electric power density for air-recirculation systems in the surrounding ISO-Cleanliness-Class-4 cleanroom was 10.2 W/ft^2 (or 110 W/m^2). As a result, the overall electric power density of the air-recirculation systems for the stand-alone open-looped minienvironments and the ISO-Cleanliness-Class-4 cleanroom as a whole was therefore estimated to be 13.4 W/ft^2 (or 145 W/m^2).

The following includes two approaches in estimating the magnitude of energy savings by implementing energy efficient minienvironments and integration them with a surrounding cleanroom of various grades of cleanroom cleanliness. The first approach, termed “case-based,” is based upon the measurements from this case study, while the second approach, termed “design-based,” is based upon the assumptions for various designs and measurements from the relevant studies, including this case study.

6.1 Case-based Estimation

Based upon measurements from this case study, overall electric power density of 13.4 W/ft^2 (or 145 W/m^2) for the minienvironments and the cleanroom as a whole was used as the base case for performance comparison.

First, improving the energy efficiency of the minienvironments would create energy-saving opportunities for the overall cleanroom facility. For example, assuming that 40-50% reduction in the minienvironments’ power demand would be possible, the electric power savings would be approximately 10-12% compared to the base case, as is illustrated in Appendices. Second, if the electric power density of the fans for cleanroom recirculation air could be reduced by one-third, the overall power savings resulting from implementing the minienvironments and reduced fan power would be 25%.

In another scenario, if the minienvironments were to operate within a non-cleanroom space, meaning that the surrounding cleanliness level (ISO-Cleanliness-Class 4) was not implemented, the overall power savings resulting from implementing the minienvironments and reduced fan power (e.g., office environment) would be approximately 61%. This estimate illustrates that significant energy savings can be achieved by eliminating surrounding cleanliness requirement (i.e., the requirement for ISO-Cleanliness-Class-4 cleanroom cleanliness being relinquished) while assuming that the effective contamination control in ISO-Cleanliness-Class-3 minienvironments could be achieved. The challenge, however, lies in whether or not it is feasible to undergo such change. For example, such a change could be that all processes were to be carried out in minienvironments, which at the same time achieve effective contamination control.

6.2 Design-based Estimation

Previous studies indicated that the fan-power density of air recirculation systems in cleanrooms tended to go up with tighter requirements for ISO Cleanliness Class [20]. For example, the fan-power densities of a group of ISO-Cleanliness-Class-4 cleanrooms ranged from 16 W/ft^2 to 38 W/ft^2 (172 W/m^2 to 409 W/m^2), with an average of approximate 30 W/ft^2 (320W/m^2). This range was generally higher than that of the group of ISO-Cleanliness-Class-5 cleanrooms, which equaled to 13.2 W/ft^2 (142 W/m^2) [20]. The fan-power densities of cleanrooms and minienvironments are listed in the Appendices. Because there was no measured data of the fan power density for an ISO-Cleanliness-Class-3 cleanroom, a simplified assumption is taken here, i.e., an ISO-Cleanliness-Class-3 cleanroom was designed to have a fan-power density of 38 W/ft^2 (409 W/m^2), which was the upper range of the ISO-Cleanliness-Class-4 cleanrooms previously studied.

Assuming an ISO-Cleanliness-Class-3 cleanroom is designed with no additional ISO-Cleanliness-Class-3 minienvironment in the facility, we may use this as the base case to estimate energy savings from various designs that would implement minienvironments. For example, we may estimate the energy savings from implementing ISO-Cleanliness-Class-3 minienvironments in such a cleanroom while making the surrounding cleanroom less stringent in terms of its ISO Cleanliness Class (e.g., from Class 3 to Class 4, Class 5, or non-cleanroom, respectively).

If the minienvironments occupy 12% of the total cleanroom floor while they were to operate within an ISO-Cleanliness-Class 4 cleanroom, the overall power savings resulted from implementing the minienvironments and the change in cleanliness requirement (thus reduced fan power) would be approximately 13%. Similarly, if they were to operate within an ISO-Cleanliness-Class 5 cleanroom, the overall power savings due to the minienvironment implementation would be approximately 57%. Furthermore, if they were to operate within a non-cleanroom space, meaning that the surrounding cleanliness level is not implemented, the overall power savings from implementing the minienvironments and largely reduced fan power (e.g., office environment) would be approximately 86%. This estimate illustrates that eliminating cleanliness requirements for the surrounding space (i.e., the requirement for ISO-Cleanliness-Class-3 cleanliness being relinquished) while maintaining the effective contamination control within the ISO-Cleanliness-Class-3 minienvironments could result in significant energy savings.

In the case study, electric power density of air-recirculation systems in the ISO-Cleanliness-Class-4 cleanroom was measured as 10 W/ft^2 (or 110 W/m^2). In this ISO-Cleanliness-Class-4 cleanroom, a number of minienvironments were located. The measured electric power density of the air-recirculation systems was much lower compared to the group of ISO-Cleanliness-Class-4 cleanrooms with a range of 16 W/ft^2 to 38 W/ft^2 (172 W/m^2 to 409 W/m^2) in a previous study [20]. The results illustrate that the electric power savings from adopting the same ISO-Cleanliness-Class-3 minienvironments and reducing the power density of air recirculation systems in the surrounding cleanroom could become even greater.

6.3 Summary of the Discussion

In summary, reducing the electric power density of the cleanroom, implementing energy-efficient minienvironments, and optimizing facility design can collectively contribute to energy savings from operating clean spaces.

Specifically, reducing the fan power density as well as optimize floor area of the minienvironments and cleanrooms can lead to overall energy savings. Because of the much smaller minienvironment volume compared to that of full-scale cleanrooms (e.g., ballroom), the amount of airflow supplied to the minienvironments for any given time could be significantly reduced. This may present potential opportunities for a significant overall energy savings because of the vastly smaller volumes of airflow that must be moved, conditioned, and filtered within a given time.

In general, in order to create opportunities for significant overall energy savings, measures should be taken to reduce fan power for both minienvironments and cleanrooms. Based upon this study, the following approaches are recommended:

- Reduce electric power demand of the minienvironments.
    - Optimize minienvironment operation, e.g., reduce the airflow and pressurization inside the minienvironments.
    - Optimize the minienvironment design, e.g., geometry and size.
    - Improve the energy efficiency of minienvironment air systems, e.g., FFU efficiency.
- Reduce electric power demand of the primary cleanroom housing the minienvironments.
    - Optimize the control of airflow rate, air-change rates, and pressurization.
    - Optimize the type and size of recirculation air systems.
    - Adopt variable-speed-drive motors in air systems.
    - Minimize air system resistance.
    - Optimize the size and cleanliness class of clean space.

7. Conclusions and Recommendations

Through literature reviews and the interactions with industry in the project, it is clear that there has been some movement in how the industry approaches the design and retrofits of cleanroom facilities used in microelectronics, i.e., toward adopting minienvironments as an emerging technology to achieve effective contamination control. In addition, similar shift is being observed in facilities for manufacturing drugs, medical device, and other healthcare products, such as using separative devices, bio-safety cabinets, glove boxes, etc. When being appropriately implemented and integrated with large cleanrooms, minienvironments may present many advantages such as better control, facility integration, and lower airflow rates required for a similar production output.

Prior to this case study including the previous study [3][4], there was virtually no quantitative information that was publicly available to provide knowledge or scientific understanding of the energy performance of minienvironments in operation. This case study has further provided quantitative data to characterize the energy performance of minienvironments. The results have been presented to industry stakeholders including electric utility company, cleanroom facility engineers or managers, and consultants in contamination control (see Appendix on the summary of a workshop).

The following enlists the conclusions drawn from the study and recommendations for future work.

7.1 Conclusions

This study investigated energy and environmental performance of ISO-Cleanliness-Class-3 minienvironments housed in a traditional, larger ISO-Cleanliness-Class-4 cleanroom used in the microelectronic industry. The measured parameters included electric power demand for minienvironments as compared to cleanrooms of various cleanliness grades. The study also estimated energy-saving potential of the design, operation, and management of clean spaces when minienvironments were integrated with a traditional, large cleanroom. Based upon the experimental measurements, analysis, and discussion in this case study, the following conclusions are made:

- Energy efficiency levels of the minienvironments in this study were found to be lower when compared with their cleanroom counterparts. Optimal contamination control for minienvironments could be realized by optimizing minienvironment design, regulating airflow rates and/or air-pressure differentials between minienvironment space and its surrounding space to achieve effective and efficient particulate filtration control.

- Minienvironments selected in this study were effective in maintaining particle-concentration levels within what was intended. In addition, the minienvironments exhibited variations in physical sizes, airflow speeds, air-change rates, energy performance index, and electric power density, while air-pressure differentials between minienvironment space and its surrounding space were considerably lower than the IEST recommended guideline and the rule of thumbs.

- Optimizing the required airflow rates for minienvironments and the surrounding cleanroom could result in energy savings. For example, providing the minienvironment with the much smaller volumes of air that must be moved, conditioned, and filtered in a given time. Additional energy savings could be achieved through reducing electric power demand of recirculation systems in the surrounding cleanroom space.

- Adopting the minienvironment concept as a means of contamination control will continue to influence the future design, construction, and operation of cleanroom spaces. Successfully applying minienvironments to create large potential energy savings is, however, an emerging concept for improved energy efficiency, if not new.

7.2 Recommendations

This case study characterized the energy performance of selected minienvironments with the assumption that they were all operating at steady states. In actual applications, it is possible that additional factors, e.g., non-steady-state operation, could make this assumption invalid for certain circumstances. Additional investigation and research is necessary for further understanding the minienvironment technology, and to realize the energy-saving potentials by applying minienvironments in cleanroom contamination control.

Recommendations for future investigations and improvement in energy-efficiency practice include the following:

- Develop methods and approaches to determine the cleanliness requirements for contamination control for both minienvironments and the surrounding cleanroom. Optimal cleanliness levels shall meet minimal particle retaining requirements, but should not be more stringent than what the process occurring in the cleanroom requires.

- Examine and understand acceptable ranges of airflow speeds and air-change rates in minienvironments, and their association with cleanliness levels. Develop optimal airflow rates in the surrounding cleanroom areas, and where possible, reduce supply airflow rates. Using optimal air-change rates will allow designers to lower construction costs as well as to reduce energy costs while maintaining the level of air cleanliness required in cleanroom facilities.

- Investigate and understand acceptable ranges of pressure differential between minienvironments and the surrounding spaces, e.g., optimal airflows through the minienvironments.

- Develop scientific basis of optimal designs and demonstrate energy-saving opportunities of adopting minienvironments as an emerging technology in effective contamination control and develop strategies to improve energy savings.

- Develop additional case studies or benchmarking studies to quantify energy and environmental performance of minienvironment systems in various applications, e.g., separative device, enclosure, glove box, bio-safety cabinet used in different industries.

- Develop scientific understanding of how to improve the effectiveness and energy efficiency of the minienvironment systems including energy efficient fan-filter units and optimal speed control in such applications. Develop approaches and methods to understand and improve filtration effectiveness and energy efficiency.

- Develop information and understanding of dynamic behavior of particle contaminants in minienvironments and the surrounding cleanroom as a function of relevant parameters (e.g. particle size, volatile organic compound, airborne molecular contaminants, etc.) and airflow conditions (e.g., design, pressure differential, human movement, product movements, heat), and its impact on energy management.

- Use computational-fluid-dynamics (CFD) modeling, particle-count monitoring, and experiments as the tools to evaluate the environmental and energy performance of minienvironments, and to assist in the design process, qualification, and validation in actual cleanroom/minienvironment planning and operation.

- Develop and disseminate scientific information on particulate contamination, including temporal and spatial dispersion of contaminants, effectiveness of HEPA/ULPA filters in particle-concentration control, and its relevance to the energy performance of air-delivery systems in clean spaces.

- Develop market information or surveys on the industries and scientific communities using minienvironment concepts and investigate such applications to quantify energy-savings potential.

- Integrate the new knowledge and information in national or international guiding documents in future editions, such as ANSI-accredited IEST RP 28.1 – Minienvironments, to maximize its usefulness and to benefit sustainable development of the industries using minienvironments.

8. Acknowledgements

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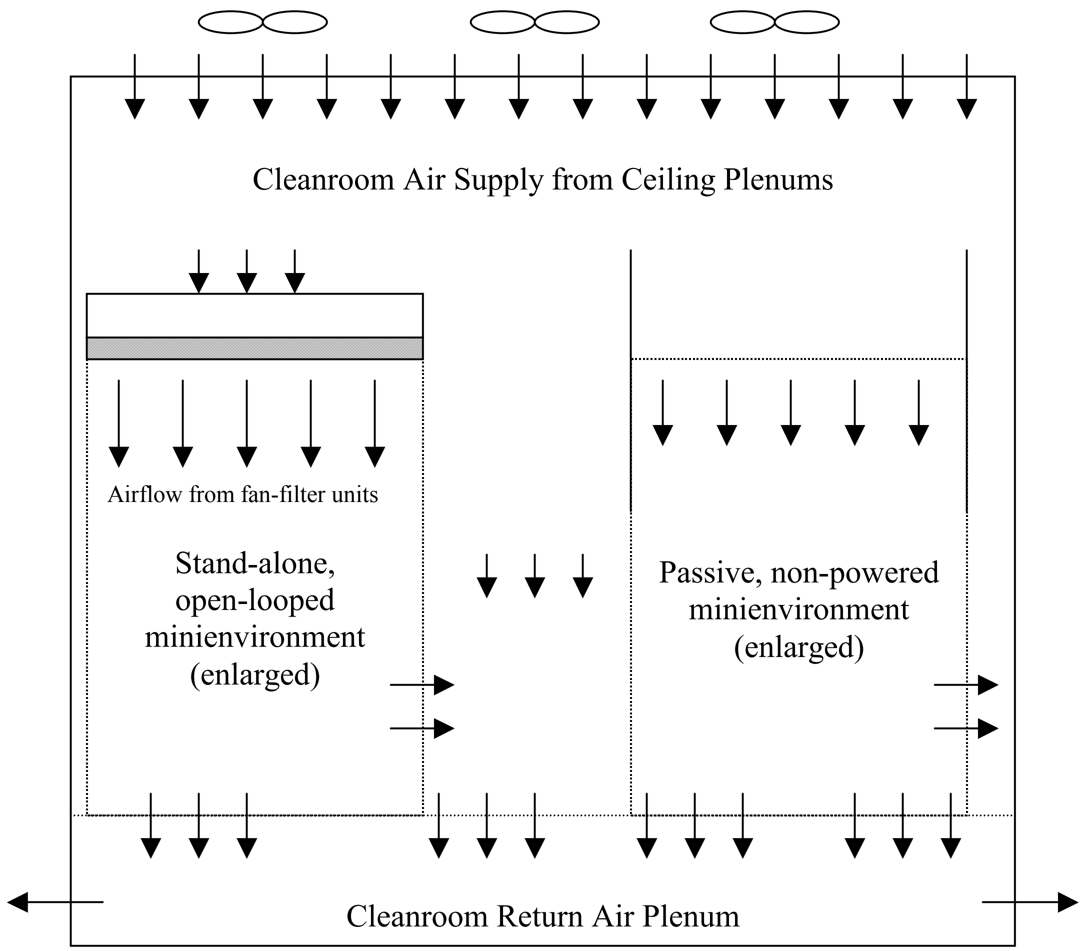
10. Appendices

10.1 Appendix - Schematic Diagram of Minienvironments in the Cleanroom



10.2 Appendix - Case-Based Estimate of Energy-savings

Case Study Based	Floor Area (ft^2) / (m^2)	Total Electric Power (kW)	Electric Power Density (W/ft^2)/(W/m^2)	Estimated Energy-savings
ISO-Cleanliness-Class-3 Minienvironment	424/39	12.0	28.3/304	-
ISO-Cleanliness-Class-4 Cleanroom	3680/342	37.5	10.2/110	-
ISO-Cleanliness-Class-4 Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	49.5	13.4/145	Base case
ISO-Cleanliness-Class-4 Cleanroom and Improved ISO-Cleanliness-Class-3 Minienvironment (by 50%)	3680/342	43.5	11.8/127	12%
Improved ISO-Cleanliness-Class-4 Cleanroom (by 33%) and ISO-Cleanliness-Class-3 Minienvironment	3680/342	37.0	10.1/108	25%
Non-Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	12.0	5.3/57	61%

10.3 Appendix - Design-Based Estimate of Energy-savings

Design based	Floor Area (ft^2) / (m^2)	Total Electric Power (kW)	Electric Power Density (W/ft^2) / (W/m^2)	Estimated Energy-savings
ISO-Cleanliness-Class-3 Minienvironment @12% occupancy	424/39	12.0	28.3/304	-
ISO-Cleanliness-Class-3 Cleanroom	3680/342	139.8	38.0/409	Base case
ISO-Cleanliness-Class-4 Cleanroom	3680/342	109.3	29.7/320	-
ISO-Cleanliness-Class-5 Cleanroom	3680/342	48.6	13.2/142	-
ISO-Cleanliness-Class-4 Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	121.3	33.0/355	13%
ISO-Cleanliness-Class-5 Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	60.6	16.5/177	57%
Non-Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	19.3	5.3/57	86%

10.4 Appendix - Summary of the Workshop on Minienvironment

LBNL developed and conducted a workshop based upon the case studies on minienvironments. The workshop was titled "Trends in Cleanroom Technology and Energy Savings Opportunities," and was organized in collaboration with PG&E and the city of San Jose. It was held in San Jose Martin Luther King Library, on September 13, 2005. The subtitle of the workshop was termed as "Best Practices for Energy Efficient Design, Construction and Operation of Minienvironment/Cleanroom."

10.4.1 Outline of the Minienvironment Workshop

Lawrence Berkeley National Laboratory, the California Energy Commission, Pacific Gas and Electric Company hosted a special workshop on the best practices for energy efficient clean spaces, using minienvironments that are gaining popularity in a wide range of industries.

A minienvironment is a localized (usually minimized) clean environment created by an enclosure to isolate a product or process from the surrounding environment. It carries various names, such as Separative device, safety cabinet, isolator, etc. The goal of the Minienvironment Workshop was to provide a forum for sharing knowledge and to stimulate discussion among participants about emerging technologies and strategies of achieving energy efficiency while maintaining effective contamination control in cleanrooms.

This workshop was designed for suppliers, end-users, designers, facility managers, consultants, and strategic managers. The participants included utility managers, facility engineers, facility managers, consultants, and users.

10.4.2 Topics Covered in the Minienvironment Workshop

- A preview of R&D activities in Minienvironment and Cleanroom Contamination Control sponsored by California Energy Commission PIER program. Presenter: Paul Roggensack, PE, California Energy Commission, Calif.

- Case Studies on Minienvironment Energy Performance: Approaches, Findings, Opportunities, and Recommendations. Presenter: Dr. Tengfang Xu, PE, Lawrence Berkeley National Laboratory, Berkeley, Calif.

- Best Practice and Lessons Learned from Minienvironment Planning and Installation. Presenter: Michael D. Jue, PE, Jazz Semiconductor, Newport Beach, Calif.

- Energy Efficiency Programs in Calif. Presenter: Bill Dunckel, PG&E, San Francisco, Calif.

10.4.3 Participant Forum on Minienvironments

Forum Leader: Dr. Tengfang Xu, PE, Lawrence Berkeley National Laboratory, Berkeley, Calif.

The participants as a group discussed the industrial trends, emerging cleanroom technologies, and strategies for better efficiency in cleanrooms. The concept of Efficient and Effective (E^2) Minienvironment proposed and presented by Dr. Xu was well received and supported by the participants.

The team discussed the significance of and explored the future opportunities in energy efficiency and sustainable development in controlled environments. The team provided suggestions about how to make LBNL's research on E^2 minienvironment known to a wider range of industries. The consensus from the team discussion included 1) Enhancing the visibility of LBNL's research and case studies will be necessary through further marketing to various industries; 2) Collaboration among industries including users, suppliers, utility companies, and government entities such as CEC will be important to facilitate the applications of research and technology, and 3) Further R&D investigations and activities as outlined in the recommended list will be necessary and important for the future success in promoting E^2 minienvironments in cleanroom applications.

10.4.4 Workshop Presentation and Recommendations from the Case Studies (Power Point slides)